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Miocene–Pliocene planktonic foraminiferal biostratigraphy of the Pearl River Mouth Basin, northern South China Sea

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Abstract The present study deals with the planktonic foraminiferal biostratigraphy of the Miocene–Pliocene sequence of three petroleum exploration wells (BY7-1-1, KP6-1-1 and KP9-1-1) in the Pearl River Mouth Basin (PRMB). In general, the three wells contain a fairly well-preserved, abundant foraminiferal fauna. The proposed planktonic foraminiferal zonation follows the scheme updated by Wade *et al*. (2011). Nineteen planktonic foraminiferal zones have been recognized, 14 zones (zones M1–M14) for the Miocene and 5 zones (zones PL1–PL5) for the Pliocene. The zonation is correlated with previously published biostratigraphic subdivisions of the Neogene succession in the PRMB and with international foraminiferal zonations. The zonal boundaries are mostly defined by the last appearance datum of zonal taxa of planktonic foraminifera, which is more reliable than the FAD (first appearance datum) events for ditch cutting sampling. Changes in the coiling of *Globorotalia menardii* (s. l.) are also used to define the zonal boundaries, where no LADs (last appearance datum) are available. The *Fohsella fohsi* group, comprising useful taxa for delimiting zonal boundaries of the middle Miocene in other areas, has a poor record within the Pearl River Mouth Basin due to unfavorable ecological conditions, and cannot be used for the studied wells. Different from the previously reported zonal scheme for the PRMB, the present zonation is based on correlation with the current standard planktonic foraminiferal zonation, with calibrated absolute ages.

Key words Planktonic foraminifera, zonation, Neogene, Pearl River Mouth Basin

1 Introduction

The Pearl River Mouth Basin (PRMB, 111°–118°E, 19°–23°N) is located in the eastern part of the northern continental shelf of the South China Sea. It is 750 km long and 300 km wide and covers an area of about 175,000 km^2 (Jin *et al*., 1984; Jiang *et al*., 1994; Jin, 2005). It is a rifted continental marginal basin running in a NE–SW direction, formed during early Cenozoic time. The basin is composed of the Northern Depression Zone, Central Uplift Zone, and Southern Depression Zone (Jiang *et al*., 1994). It is bordered to the north by the Hainan Uplift and Northern Faulted Terraces and to the south by the bedrock uplift (in the western part) and igneous rock zone (in the eastern part). The Paleogene to Neogene sediments are well developed in the basin, have a thickness of over 10,000 m, and provide favourable conditions

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for oil generation and accumulation. Consequently, the PRMB has become one of the important oil and gas energy sources of China and attracted broad attention (Jiang *et al*., 1994; Jin, 2005). Petroleum exploration has been carried out since the middle 1970's, and so far over 100 wells have been drilled, which provide a good data source for foraminiferal biostratigraphic analysis. However, academic research has been only sporadically reported. Previous studies on the Neogene planktonic foraminifera from the PRMB mainly include those of Qin (1982, 1985, 1992, 1996a), Wan *et al*. (1996a, 1996b), and Lin *et al*. (2004, 2007), which were correlating to the zonal schemes of Blow (1969, 1979) and Bolli and Saunders (1985). In this study, we present a detailed planktonic foraminiferal zonation of the Miocene–Pliocene succession in the PRMB, primarily correlating it to the standard planktonic foraminiferal zones updated by Wade *et al*. (2011). The zonation is based on data from three petroleum exploration wells. BY7-1-1 and KP6-1-1 were drilled in the Baiyun Depression of the Southern Depression Zone and KP9-1-1 was drilled at the margin of the Shenhu Uplift in the Central Uplift Zone (Fig. 1).

2 Lithostratigraphic framework

The lithostratigraphy of the Cenozoic sediments in the Pearl River Mouth Basin have been classified and discussed by many workers (*e.g*. Duan and Lei, 1984; Zeng and Zhang, 1992; Jiang *et al*., 1994; Huang and Zhong, 1996; Huang 1999; Qin, 1996a, 1996b, 2000, 2007). The classification of Qin (2000), which combined seismic data and biostratigraphic analysis (foraminifera, calcareous nannofossils, and palynomorphs), has been adopted for the present study. We focus on the stratigraphic interval from the Miocene to the Pliocene, which is divided into five formations, namely, from the oldest to the youngest, the Zhuhai Formation (Early Miocene), the Zhujiang Formation (Early Miocene), the Hanjiang Formation (Middle–Late Miocene), the Yuehai Formation (Late Miocene), and the Wanshan Formation (Pliocene) (Table 1).

3 Planktonic foraminiferal biostratigraphy

3.1 Material and methods

A total of 517 samples have been analyzed in the present study: 174 samples from Well BY7-1-1 (820–3519 m core depth), 220 samples from Well KP6-1-1 (660–2757 m core depth), and 123 samples from Well KP9-1-1 (560–1771 m core depth). The samples (about 50 g) were disaggregated with H_2O_2 (10%), washed through a 0.063 mm sieve, and followed by drying and picking. The fraction larger than 0.063 mm is used for estimating abundance, which was calculated for 100 g of sediments.

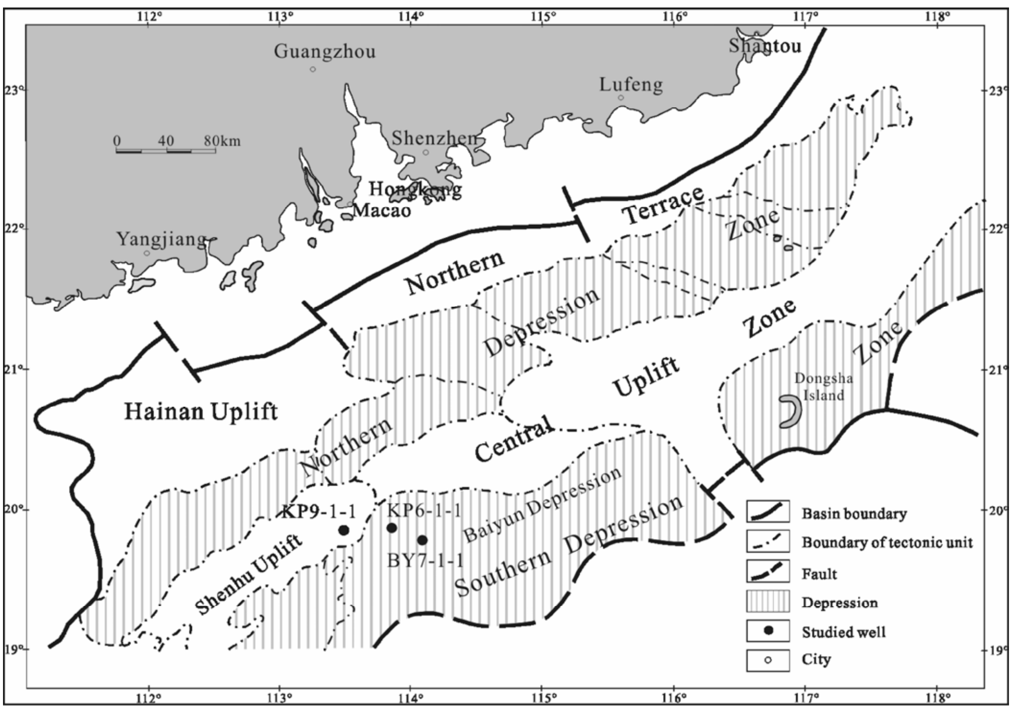

Fig. 1 Tectonic units of the Pearl River Mouth Basin, showing location of the studied wells (after Jiang *et al*., 1994; Qin, 1996b)

Table 1 Stratigraphic scheme of the Neogene succession in the Pearl River Mouth Basin (after Qin, 2000) The planktonic foraminiferal zonation proposed in this study is also presented.

Epoch		Formation	Seismic horizon	Biostratigraphic zonations: Foraminiferal zonation	Biostratigraphic zonations: Nannofossil zonation	Biostratigraphic zonations: Palynormorph assemblage	This study
Pliocene	Late	Wanshan Formation		N21 d	NN19		?
				N21 c	NN18	*Faguspollenites – Persicariolpollis* Assemblage	
				N21 b	NN17		PL5
				N21 a	NN16		PL4
				N20	NN16		PL3
	Early			N19 b	NN15		PL2
				N19 a	NN14		PL1 b
				N18	NN13		PL1 a
			T1				
Miocene	Late	Yuehai Formation		N17 d	NN12	*Graminidites – Chenopodipollis* Assemblage	M14
				N17 c	NN11		M13 b
				N17 b	NN11		M13 b
				N17 a	NN11		M13 a
				N16	NN10		M13 a
			T2				
		Hanjiang Formation		N15	NN9	*Florachuetzia levipoli – Zoocostites ramonae* Assemblage	M12
				N14	NN8		M11
	Middle			N13	NN7		M10
			T3				
				N12	NN6		M9
				N11	NN5		M8
				N10	NN5		M7
				N9	NN5		M6
				N8 b	NN4		M5 b
			T4				
	Early	Zhujiang Formation		N8 a	NN4	Dinoflage cysts – *Polypodiaceaesporites* Assemblage	M5 a
				N7	NN4		M4
				N6	NN3		M3
			T5				
				N5	NN2		M2
			T6				
		Zhuhai Formation		N4 b	NN1	Bisaccata pollen – *Alnipollenites* Assemblage	M1
				N4 a	NP25		M1
			T7				

The Miocene and Pliocene sediments of the three investigated wells generally contain fairly well-preserved planktonic foraminifera. In Well BY7-1-1, foraminifera are abundant from 820 m to 2439 m. From 2439 m downwards the record of planktonic foraminifera becomes scarce, with several barren intervals. In Well KP6-1-1, foraminifera are abundant to common from 660 m to 2329 m and rare to scarce from 2329 m to 2569 m; below 2569 m foraminifera are absent. In Well KP9-1-1, foraminifera are abundant from 560 m to 1141 m, common from 1141 m to 1510 m, and scarce from 1510 m to 1612 m. Below this level, an extended interval barren of planktonic foraminifera occurs.

The abundance of planktonic foraminifera is reported as abundant (>5000 specimens per 100 g sediment), common (500–5000 specimens per 100 g sediment), frequent (50–499 specimens per 100 g sediment), and rare (<50 specimens per 100 g sediment). The distributions of key marker species are shown in Figs. 2–4.

3.2 Planktonic foraminiferal zones

The presented planktonic foraminiferal zonation follows the scheme updated and revised by Wade *et al*., (2011), with the notation “M” for Miocene and “PL” for Pliocene zones. The zonal boundaries are mostly defined by the last appearance datum of zonal taxa of planktonic foraminifera. Many authors consider the last appearance more applicable for biostratigraphic analysis based on ditch cuttings samples (*e. g*. Mudge and Bujak, 1996; Qin, 1996a; Lin *et al*., 2004; Li *et al*., 2007a). The change in coiling direction of planktonic foraminifera has also been used as a biostratigraphic marker (*e.g*. Berggren, 1973; Qin, 1982, 1996a; Lagoe and Thompson, 1988; Chaisson and Leckie, 1993; Chaisson, 1995), even though it is

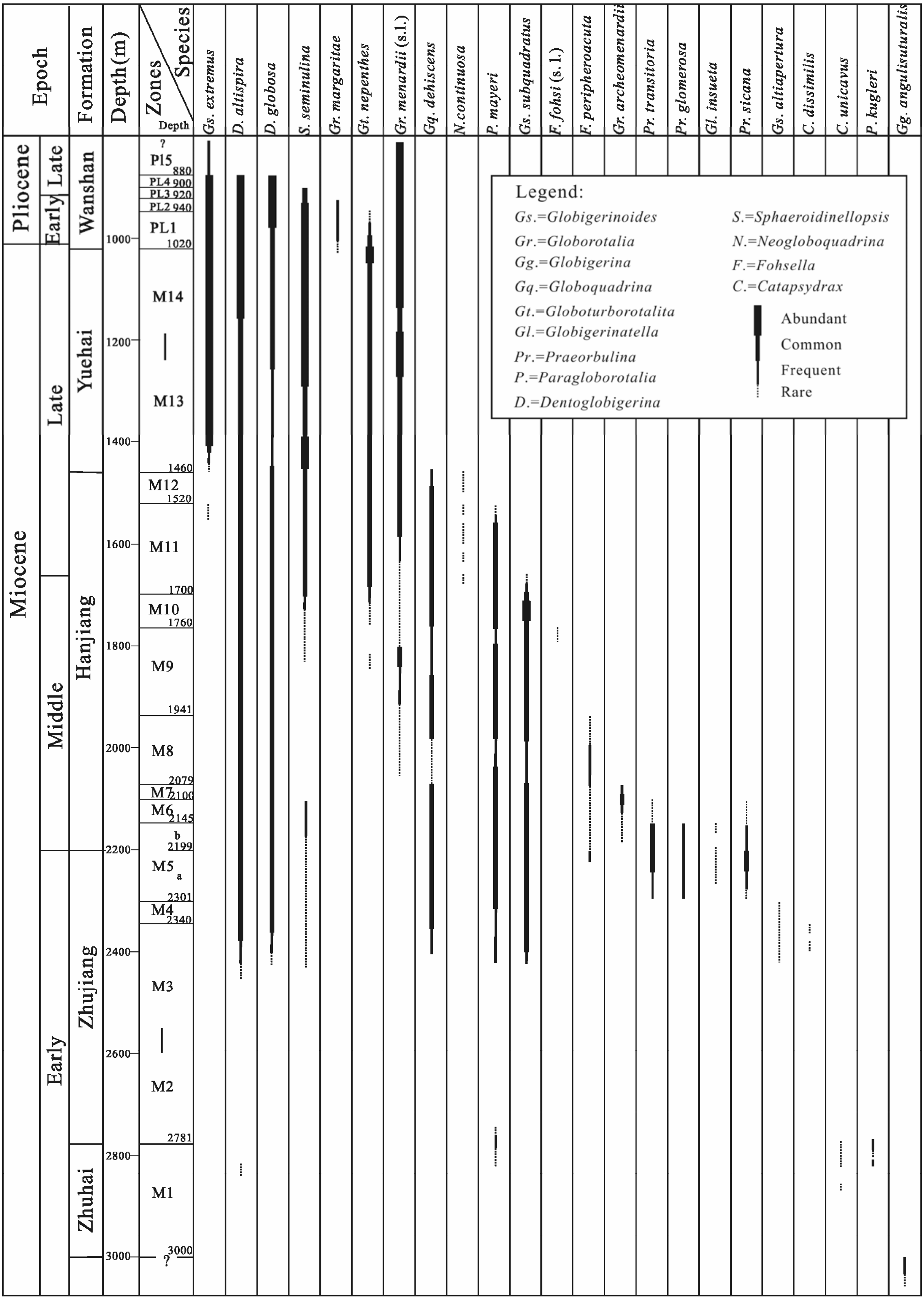

Fig. 2 Stratigraphic ranges of marker taxa of planktonic foraminifera recorded in Well BY7-1-1

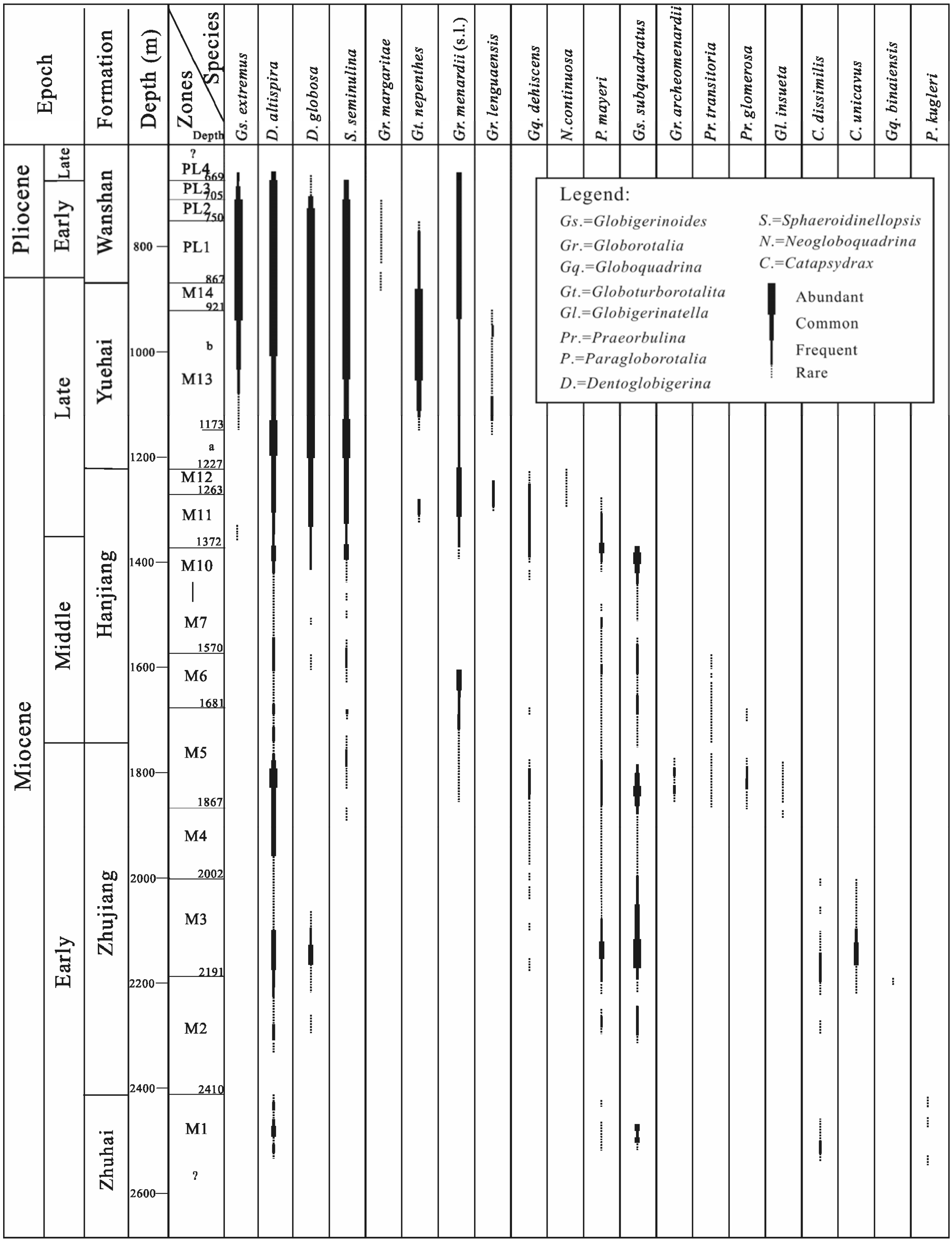

Fig. 3 Stratigraphic ranges of marker taxa of planktonic foraminifera recorded in Well KP6-1-1

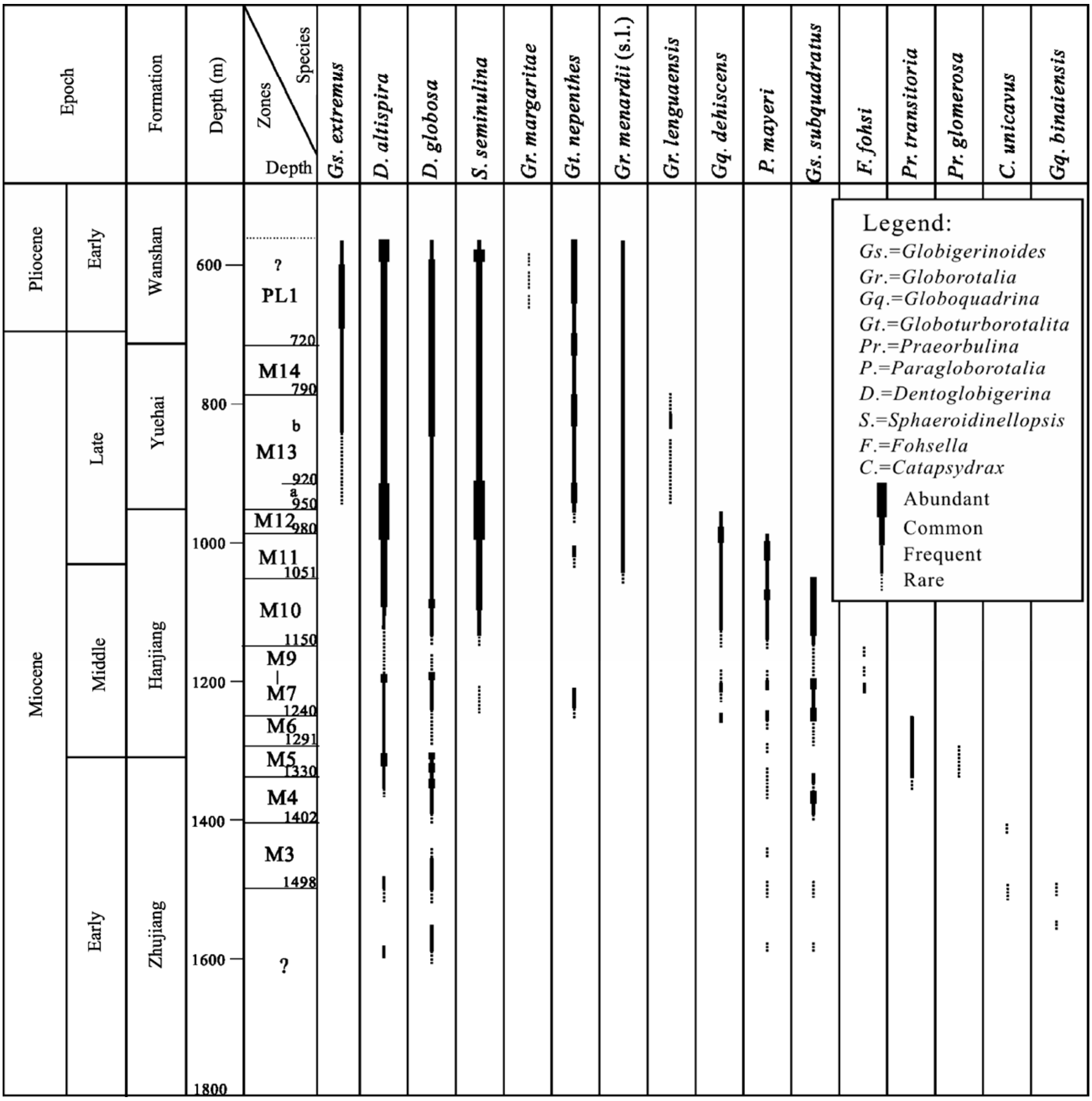

Fig. 4 Stratigraphic ranges of marker taxa of planktonic foraminifera recorded in Well KP9-1-1

thought to be influenced by the local environment (Chaisson, 1995; Liu *et al*., 2009). The coiling-change events of *Globorotalia menardii* (s.l.) can be well correlated within the PRMB and have been extensively used as a zonal boundary index (Qin, 1996a). We also take these events to define the zonal boundaries of the Late Miocene, where no last occurrence data are available. The identified zones are correlated with the equivalent standard planktonic foraminiferal zones, mainly with those updated by Wade *et al*. (2011), and with previously published planktonic foraminiferal zones within the PRMB, particularly with those of Qin (1996a) (Fig. 5). Ages of planktonic foraminiferal events are after those given in Wade *et al*. (2011), with calibration of the time scale of Lourens *et al*. (2004) that provides a more accurate chronology for the Neogene bioevents (Li *et al*., 2007b).

The following abbreviations are used in the zonal descriptions: LAD, last appearance datum; FAD, first appearance datum; and LCAD, last common appearance datum. Because the studied samples are all ditch cuttings samples, the foraminiferal zones are described from top to base.

***Zone PL5* (part)**

Definition. The top of PL5 is not reached in the stud-

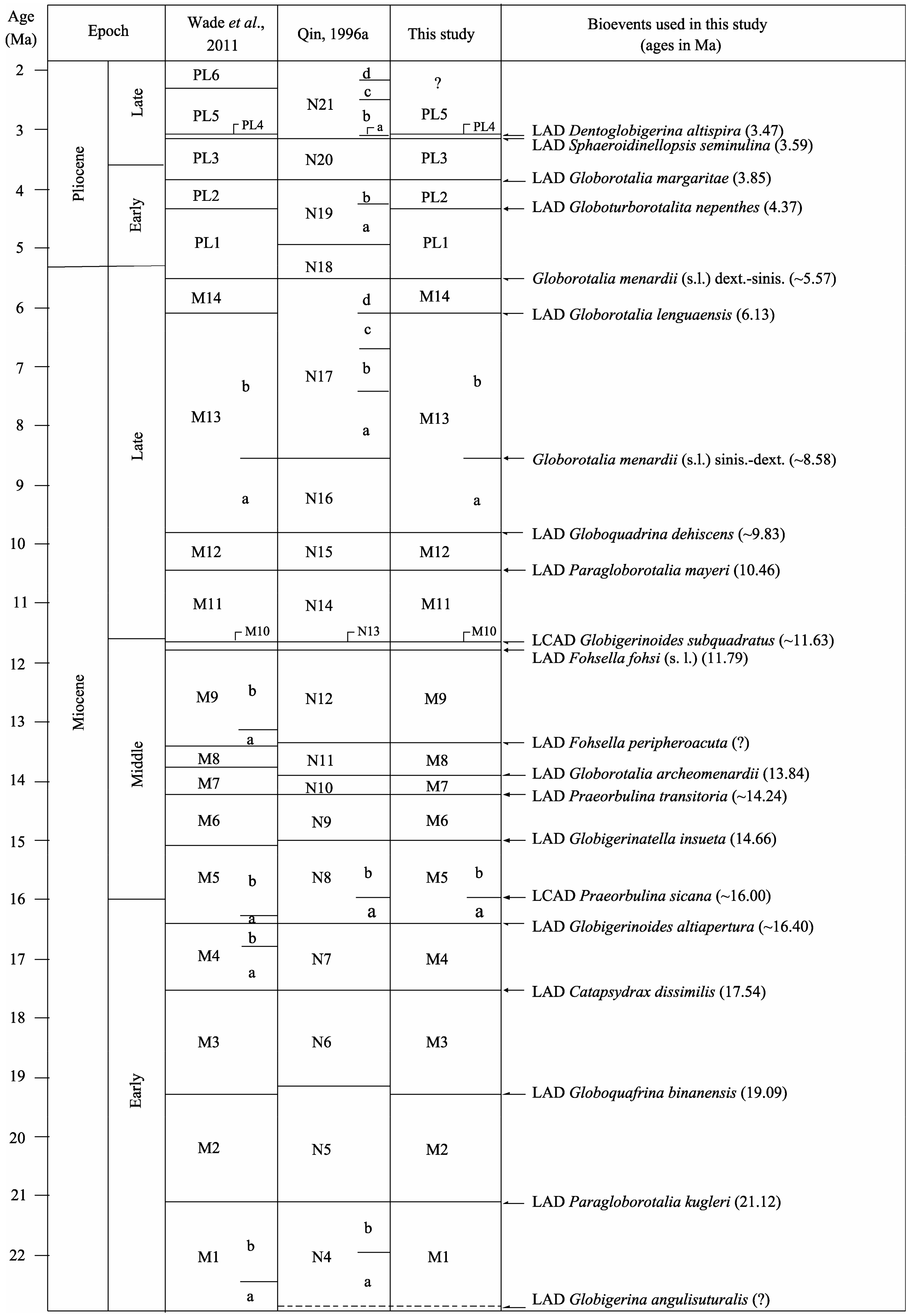

Fig. 5 Planktonic foraminiferal zonation proposed in this study compared to those of Wade *et al*. (2011) and Qin (1996a)

ied intervals. The base of PL5 is defined by the LAD of *Dentoglobigerina altispira*.

Discussion. This zone is partly recorded in Well BY7-1-1, representing the youngest planktonic foraminiferal zone identified in the studied intervals of three wells. As in Wade *et al*. (2011), the LAD of *Dentoglobigerina altispira* is taken as its base marker, which was observed at 880 m in Well BY7-1-1. This interval is equivalent to the lower part of N21b of Qin (1996a), who defined the base N21b with the LAD of *Dentoglobigerina altispira* and the top of N21b with the LCAD of *Globigerinoides extremus*. This top marker cannot be well distinguished due to the lack of samples above 820 m, where *Gs. extremus* still occurs frequently.

Occurrence. Well BY7-1-1, 820–880 m; Wanshan Formation.

Age. Late Pliocene, ?–3.47 Ma.

Zone PL4

Definition. The top of PL4 is defined by the LAD of *Dentoglobigerina altispira*. The base of PL4 is defined by the LAD of *Sphaeroidinellopsis seminulina*.

Discussion. The definition of Zone PL4 is the same as that in Wade *et al*. (2011). This zone is completely recorded in Well BY7-1-1 and partly recorded in Well KP6-1-1. The LAD of *Dentoglobigerina globosa* is coincident with the LAD of *Dentoglobigerina altispira*. Both zonal markers occur abundantly. This zone is equivalent to N21a of Qin (1996a), which was defined with the same boundary criteria. In contrast , the LADs of *Dentoglobigerina altispira* and *Sphaeroidinellopsis seminulina* were recorded together from the lower part of N21 at ODP Site 1143 in the southern South China Sea (Li *et al*., 2005), which might be due to a low sedimentation rate.

Occurrence. Well BY7-1-1, 880–900 m; Well KP6-1-1, ? – 669 m; Wanshan Formation.

Age. Late Pliocene, 3.47–3.59 Ma.

Zone PL3

Definition. The top of PL3 is defined by the LAD of *Sphaeroidinellopsis seminulina*. The base of PL3 is defined by the LAD of *Globorotalia margaritae*.

Discussion. The definition of Zone PL3 is the same as that of Wade *et al*. (2011). This zone can be observed in Wells BY7-1-1 and KP6-1-1. The zonal marker *Sphaeroidinellopsis seminulina* occurs commonly during this zonal interval. The interval is equivalent to N20 of Qin (1996a), which is defined by the same boundary criteria.

Occurrence. 900–920 m in Well BY7-1-1; 705–669 m in Well KP6-1-1; Wanshan Formation.

Age. Early–Late Pliocene, 3.59–3.85 Ma.

Zone PL2

Definition. The top of PL2 is defined by the LAD of *Globorotalia margaritae*. The base of PL2 is defined by the LAD of *Globoturborotalita nepenthes*.

Discussion. The definition of Zone PL2 is the same as that in Wade *et al*. (2011). The zonal marker *Globorotalia margaritae* is frequent in Well BY7-1-1 and rare in Wells KP6-1-1 and KP9-1-1. This species has a short stratigraphic range in the study area. A change in coiling preference (sinistral–dextral) of *Pullaniatina* spp. was found during this zone interval, which was calibrated to 4.08 Ma by both Lourens *et al*. (2004) and Chaisson and Pearson (1997). This coiling-change event was also recorded within Zone N19 in Chaisson (1995). This zone approximately correlates with N19b and the upper part of N19a of Qin (1996a), who defined the N19a/N19b boundary with the change in coiling preference of *Pullaniatina* spp..

Occurrence. 920–940 m in Well BY7-1-1, 705–750 m in Well KP6-1-1; Wanshan Formation.

Age. Early Pliocene, 3.85–4.37 Ma.

Zone PL1

Definition. The top of PL1 is defined by the LAD of *Globoturborotalita nepenthes*. The base of PL1 is defined by a change in coiling preference (dextral–sinistral) of *Globorotalia menardii* (s.l.).

Discussion. The top of Zone PL1 is defined as in Wade *et al*. (2011) by the LAD of *Globoturborotalita nepenthes*. In Wade *et al*. (2011), the base of PL1 was defined by the lowest occurrence of *Globorotalia tumida*. We take the change in the preference of coiling direction of *Globorotalia menardii* (s.l.) from dextral to sinistral as the boundary index, which is extensively recognizable in the Pearl River Mouth Basin (Qin, 1996a). The age of this coiling-change event is estimated close to that of the FAD of *Globorotalia tumida* (5.57 Ma), which is recorded near the level where the coiling change (dextral – sinistral) of *Globorotalia menardii* (s.l.) occurs in Wells BY7-1-1 and KP9-1-1, probably representing the true FAD event. Preferentially sinistrally coiled *Globorotalia menardii* (s.l.) existed only for a short period of time. They changed back to preferred dextral coiling at a slightly younger level than the base of PL1. This coiling-change event is coincident with the FAD of *Sphaeroidinella dehiscens*, which was dated to 5.53 Ma (Lourens *et al*., 2004). Both can be taken as secondary recognizable bioevents within Zone PL1. This zone is equivalent to the lower part of N19a and N18 of Qin (1996a), who defined the N19/N18 boundary with the change in coiling preference (sinistral–dextral) of *Globorotalia menardii* (s.l.). The base of PL1 is close to the Miocene/Pliocene boundary.

Occurrence. 940–1020 m in Well BY7-1-1; 750–867 m in Well KP6-1-1; in Well KP9-1-1, the base of PL1 is at 720 m, the top of PL1 is not reached; Wanshan Formation.

Age. Late Miocene–Early Pliocene, 4.37– ~5.57 Ma.

Zone M14

Definition. The top of M14 is defined by a change in coiling preference (dextral–sinistral) of *Globorotalia menardii* (s.l.). The base of M14 is defined by the LAD of *Globorotalia lenguaensis*.

Discussion. Preferentially dextrally coiled *Globorotalia menardii* (s.l.) range during zones M14 and M13. As in Wade *et al*. (2011), the LAD of *Globorotalia lenguaensis* is taken to mark the M14/M13 boundary. This zonal marker is persistently recorded in Well KP6-1-1 and Well KP9-1-1, but in Well BY7-1-1 it occurs only sporadically, and its last occurrence is difficult to recognize. This zone is equivalent to the subzone N17d of Qin (1996a), which was defined by the same criteria.

Occurrence. 1020–? m in Well BY7-1-1, 867–921 m in Well KP6-1-1, and 720–790 m in Well KP9-1-1; Yuehai Formation.

Age. Late Miocene, ~5.57–6.13 Ma.

Zone M13

Definition. The top of M13 is defined by the LAD of *Globorotalia lenguaensis*. The base of M13 is defined by the LADs of *Globoquadrina dehiscens*.

Discussion. The definition of the top of M13 is the same as that of Wade *et al*. (2011). The base of M13 is defined here by the LAD of *Globoquadrina dehiscens*, replacing *Neogloboquadrina acostaensis*, the basal marker of M13 in Wade *et al.* (2011) (see below discussion).

Zone M13 can be subdivided into the subzones M13a and M13b. Wade *et al*. (2011) defined the M13a/M13b boundary with the lowest occurrence of *Globorotalia plesiotumida*. In Well BY7-1-1, this FAD event was recorded from the same level as the change in coiling preference of *Globorotalia menardii* (s.l.) from sinistral to dextral, which is taken here as the marker of the M13a/M13b boundary and can be identified in the three studied wells (at 1410 m in Well BY7-1-1, 1173 m in Well KP6-1-1 and 920 m in Well KP9-1-1). This change in coiling preference was used to mark the N16/N17 boundary dated to 8.6 Ma by Qin (1996a), very close to the age of the M13a/M13b boundary (8.52 Ma) defined by the FAD of *Globorotalia plesiotumida* in Wade *et al.* (2011). Subzone M13b is equivalent to subzones N17a–N17c of Qin (1996a). Within the range of M13b, two changes in coiling preference of *Globorotalia menardii* (s.l.) are recorded. The lower one is the change from dextral to sinistral recorded at 1300 m in Well BY7-1-1, 1074 m in Well KP6-1-1, and 850 m in Well KP9-1-1. The upper one is the change from sinistral to dextral recorded at 1100 m in Well BY7-1-1, 975 m in Well KP6-1-1, and 830 m in Well KP9-1-1. These two events were used to mark the N17a/N17b and N17b/N17c boundaries in the PRMB by Qin (1996a). Subzone M13a is equivalent to the N16 of Qin (1996a), with the same definition.

Occurrence. ?–1460 m in Well BY7-1-1, 921–1227 m in Well KP6-1-1, and 790–950 m in Well KP9-1-1; Yuehai Formation.

Age. Late Miocene, 6.13– ~9.83 Ma.

Zone M12

Definition. The top of M12 is defined by the LAD of *Globoquadrina dehiscens*. The base of M12 is defined by the LAD of *Paragloborotalia mayeri* (=*P*. *siakensis* here).

Discussion. Wade *et al*. (2011) defined the M12/M13 boundary with the lowest occurrence of *Neogloboquadrina acostaensis*, as other authors did for the equivalent zone, such as Blow (1979) for the base of Zone N16, and Bolli and Saunders (1985) for the base of the *Gr*. *acostaensis* Zone. In all three studied wells, this species shows its first appearance coincidently with the LAD of *Globoquadrina dehiscens*. Thus, this FAD event is available here and can be also used as an alternative marker for the top of M12 in the studied wells. Some researchers have shown the LAD of *Gq*. *dehiscens* to be diachronous (Hodell and Kennett, 1986). This LAD event was dated to 5.92 Ma by Wade *et al*. (2011) and 5.8 Ma by Berggren *et al*. (1995a, 1995b). However, in the PRMB, the LAD of *Gq. dehiscens* has always been recorded from a lower level, previously dated to 10.00 Ma (Qin, 1996a), and usually has been used to mark the N16/N15 boundary. This earlier extinction event of *Gq*. *dehiscens* is supported by the record of the present study. This zone is equivalent to the N15 of Qin (1996a), which was defined by the same boundary criteria.

Occurrence. 1460–1520 m in Well BY7-1-1, 1227–1263 m in Well KP6-1-1, and 950–980 m in Well KP9-1-1; Hanjiang Formation.

Age. Late Miocene, ~9.83–10.46 Ma.

Zone M11

Definition. The top of M11 is defined by the LAD of

Paragloborotalia mayeri. The base of M11 is defined by the LCAD of *Globigerinoides subquadratus*.

Discussion. The definition of the top of M11 is the same as that of Wade *et al*. (2011). They defined the base of M11 with the lowest occurrence of *Globoturborotalita nepenthes* (dated to 11.63 Ma), so did Blow (1969, 1979) and Chaisson and Pearson (1997) for the base of N14. In Well BY7-1-1, *Gt. nepenthes* shows a sharp abundance increase at the level where the LCAD of *Globigerinoides subquadratus* occurs, and can be closely considered as an available FAD event. According to Turco *et al*. (2002), the LAD of *Gs*. *subquadratus* was recorded in the basal part of Zone N14 with the age of 11.55 Ma, nearly synchronous with the Mediterranean age (Hilgen *et al*., 2000). Wade *et al*. (2011) calibrated the age to 11.46 Ma, slightly younger than the age of FAD of *Gt. nepenthes*. We take here the LCAD of *Gs*. *subquadratus* to mark the base of M11, which occurs at a lower level than the LAD of *G*s. *subquadratus* and can be approximately correlated with the base of M11 of Wade *et al*. (2011). This zone is equivalent to the N14 of Qin (1996a), with the same boundary criteria.

Occurrence. 1520–1700 m in Well BY7-1-1, 1263–1372 m in Well KP6-1-1, and 980–1051 m in Well KP9-1-1; Hanjiang Formation.

Age. Middle–Late Miocene, 10.46– ~11.63 Ma.

Zone M10

Definition. The top of M10 is defined by the LCAD of *Globigerinoides subquadratus*. The base of M10 is defined by the LAD of *Fohsella fohsi* (s.l.).

Discussion. The zonal marker *Globigerinoides subquadratus* is common to abundant during the range of this zone, and its abundance clearly decreases downwards and upwards. The evolutionary lineage of *Fohsella fohsi* was usually used to delimit foraminiferal zones of the Middle Miocene in low latitude areas (*e.g*. Blow, 1969, 1979; Kennett and Srinivasan, 1983; Bolli and Saunders, 1985; Berggren *et al*., 1995b; Pearson and Chaisson, 1997; Turco *et al*., 2002; Wade *et al*., 2011). However, the environmental conditions of the PRMB were likely not optimal for the development of the *F*. *fohsi* group. Only sporadic specimens are recorded in Well BY7-1-1 and Well KP9-1-1. Due to the absence of other zonal indices, we temporarily take the LAD of *Fohsella fohsi* (s.l.) to mark the base of Zone M10. This zone is equivalent to the N13 of Qin (1996a) with the same boundary criteria, and approximately correlates with M10 of Wade *et al*. (2011).

Occurrence. 1700–1760 m in Well BY7-1-1, 1372–? m in Well KP6-1-1, and 1051–1150 m in Well KP9-1-1; Hanjiang Formation.

Age. Middle Miocene, ~11.63– ~11.79 Ma.

Zone M9

Definition. The top of M9 is defined by the LAD of *Fohsella fohsi* (s.l.). The base of M9 is defined by the LAD of *Fohsella peripheroacuta*.

Discussion. As mentioned above, the *Fohsella fohsi* lineage is not well developed in the studied wells. It is particularly inapplicable to use the FADs of the *F*. *fohsi* lineage for identifying the lower boundaries of zones M7, M8, and M9 as in Wade *et al*. (2011). The basal marker of M9 is here substituted by the LAD of *Fohsella peripheroacuta*, which was only observed in Well BY7-1-1. This event was recorded as slightly younger than the base of Zone M9 (13.41 Ma) in Wade *et al*. (2011). This zone is equivalent to N12 of Qin (1996a), which was defined by the same boundary criteria.

Occurrence. 1760–1941 m in Well BY7-1-1, 1150–? m in Well KP9-1-1; Hanjiang Formation.

Age. Middle Miocene, ~11.79 –? Ma.

Zone M8

Definition. The top of M8 is defined by the LAD of *Fohsella peripheroacuta*. The base of M8 is defined by the LAD of *Globorotalia archeomenardii*.

Discussion. The zonal marker *Fohsella peripheroacuta* is rare, but is persistently present throughout this interval in Well BY7-1-1. The LAD of *Globorotalia archeomenardii* is here taken to mark the base of Zone M8. The age of this event was revised to 13.87 Ma by Turco *et al*. (2002) and Lourens *et al*. (2004), and to 13.84 Ma by Wade *et al*. (2011), which is very close to the age of the FAD of *Fohsella praefohsi* (13.77 Ma), the top marker of M7 in Wade *et al*. (2011). This zone is equivalent to the N11 of Qin (1996a).

Occurrence. 1941–2079 m in Well BY7-1-1; Hanjiang Formation.

Age. Middle Miocene, ?–13.84 Ma.

Zone M7

Definition. The top of M7 is defined by the LAD of *Globorotalia archeomenardii*. The base of M7 is defined by the LAD of *Praeorbulina transitoria*.

Discussion. The top of M7, marked by the LAD of *Globorotalia archeomenardii*, can only be recognized in Well BY7-1-1. In Well KP6-1-1, its disappearance occurs at the same level as the lowest occurrence of *Orbulina suturalis* that was used as the basal marker of M6 by Wade *et al*. (2011) and thus does not represent the true

LAD event. The base of M7 is here delimited by the LAD of *Praeorbulina transitoria*, the age of which is estimated to be close to that of the FAD of *Fohsella peripheroacuta* (14.24 Ma) (see below), the base marker of Zone M7 of Wade *et al*. (2011). This zone is equivalent to the N10 of Qin (1996a).

Occurrence. 2079–2100 m in Well BY7-1-1, ?–1570 m in Well KP6-1-1, and ?–1240 m in Well KP9-1-1; Hanjiang Formation.

Age. Middle Miocene, 13.84– ~14.24 Ma.

Zone M6

Definition. The top of M6 is defined by the LAD of *Praeorbulina transitoria*. The base of M6 is defined by the LAD of *Globigerinatella insueta*.

Discussion. Qin (1996a) used the LADs of *Praeorbulina transitoria* and *Pr*. *sicana* to mark the N9/N10 boundary. However, *Pr*. *transitoria* shows its disappearance at a younger level than *Pr. sicana* in the studied wells, as reported in Bolli and Saunders (1985). The LAD of *Pr. sicana* was dated to 14.53 Ma by Lourens *et al*. (2004). We estimate the age of the LAD of *Pr*. *transitoria* to be younger than that of the LAD of *P. sicana* and close to the age of the lowest occurrence of *Fohsella peripheroacuta* (14.24 Ma), the M6/M7 boundary marker of Wade *et al*. (2011). The base of M6 is marked here by the LAD of *Globigerinatella insueta*, which was dated to 14.66 Ma (Lourens *et al*., 2004), younger than the basal age of M6 of Wade *et al*. (2011) (15.10 Ma). This zone is equivalent to the N9 of Qin (1996a) and corresponds to the upper part of M6 of Wade *et al*. (2011).

Occurrence. 2100–2145 m in Well BY7-1-1, 1570–1681 m in Well KP6-1-1 and 1240–1291 m in Well KP9-1-1; Hanjiang Formation.

Age. Middle Miocene, ~14.24–14.66 Ma.

Zone M5

Definition. The top of M5 is defined by the LAD of *Globigerinatella insueta*. The base of M5 is defined by the LAD *Globigerinoides altiapertura*.

Discussion. The LAD of *Globigerinatella insueta* was used by Bolli and Saunders (1985) to mark the base of the *Globorotalia peripheroronda* Zone, corresponding to the N9 of Blow (1969, 1979). However, Blow (1969) and Berggren *et al*. (1995b) argued that the FAD of *Orbulina suturalis* provides a more widespread and easily recognizable datum event than the LAD of *Gl*. *insueta* for denoting the base of N9 (M6). Wade *et al*. (2011) also used the FAD of *Orbulina suturalis* to mark the M5/M6 boundary, dated to 15.10 Ma. As mentioned above, the LAD events are more reliable for a biostratigraphic analysis based on cuttings samples, thus we still take here the LAD of *Gl*. *insueta* to mark the M5/M6 boundary, which is slightly younger than the top of M5 of Wade *et al*. (2011). The LAD of *Praeorbulina glomerosa* was considered to occur near the LAD of *Gl*. *insueta* in the PRMB (Qin, 1996a) and taken as an alternative marker for the top of M5 for Wells KP6-1-1 and KP9-1-1.

We take here the LAD of *Globigerinoides altiapertura*, instead of the FAD of *Praeorbulina sicana*, to mark the base of Zone M5. These two events were recorded at the same level in Pearson and Chaisson (1997). In Well BY7-1-1, the FAD of *Praeorbulina sicana* occurs immediately following the LAD of *Globigerinoides altiapertura*, also providing evidence that these two events may be nearly coincident.

This zone is equivalent to Zone N8 of Qin (1996a), which was subdivided into subzones N8a and N8b. The subzonal boundary has been marked by the LADs of *Fohsella birnageae* and *Globorotalia semivera* or by the LCAD of *Praeorbulina sicana*, dated to 16.00 Ma. *Fohsella birnageae* and *Globorotalia semivera* are not found in the studied wells. In Well BY7-1-1, the LCAD of *Praeorbulina sicana* is recognizable at 2199 m, which can be taken as the marker of the M5a/M5b boundary.

Occurrence. 2145–2301 m in Well BY7-1-1, 1681–1867 m in Well KP6-1-1, and 1291–1330 m in Well KP9-1-1; Zhujiang Formation–Hanjiang Formation.

Age. Early–Middle Miocene, 14.66– ~16.40 Ma.

Zones M4

Definition. The top of M4 is defined by the LAD of *Globigerinoides altiapertura*. The base of M4 is defined by the LAD of *Catapsydrax dissimilis*.

Discussion. The zonal marker *Globigerinoides altiapertura* is rare, but recorded persistently in Well BY7-1-1. Due to the absence of *Globigerinoides altiapertura* in Wells KP6-1-1 and KP9-1-1, the top of M4 is tentatively delimited by the FADs of *Praeorbulina glomerosa* and *Pr. sicana*. The base of M4 is marked here by the LAD of *Catapsydrax dissimilis*, which was also used as marker for the base of M4 (Wade *et al*., 2011), the base of N7 (Blow, 1969; 1979), and the base of the *Globigerinatella insueta* Zone (Bolli and Saunders, 1985). This zone is equivalent to the N7 of Qin (1996a).

Occurrence. 2301–2340 m in Well BY7-1-1, 1867–2002 m in Well KP6-1-1, and 1330–1402 m in Well KP9-1-1; Zhujiang Formation.

Age. Early Miocene, ~16.40–17.54 Ma.

Zone M3

Definition. The top of M3 is defined by the LAD of

Catapsydrax dissimilis. The base of M3 is defined by the LAD of *Globoquadrina binaiensis*.

Discussion. As reported by Pearson and Chaisson (1997), the LADs of *Catapsydrax unicavus* and *Globoquafrina praedehiscens* coincide with the LAD of *Catapsydrax dissimilis* in Wells BY7-1-1 and KP6-1-1 and can be taken as additional markers of the top of M3. Berggren *et al*. (1995b) also took the LADs of *Catapsydrax dissimilis* and *Catapsydrax unicavus* to mark the top of M3.

The LAD of *Globoquadrina binaiensis* was calibrated to 19.09 Ma by Lourens *et al*. (2004) and 19.10 Ma by Pearson and Chaisson (1997), *i.e*., slightly younger than the base of *Globigerinatella* sp. (19.30 Ma), the basal marker of M3 in Wade *et al*. (2011). The base of M3 is only recognizable in Wells KP6-1-1 and KP9-1-1, not in Well BY7-1-1 due to an extended interval containing very poor foraminiferal assemblages below 2439 m. This zone is equivalent to the N6 of Qin (1996a), which was defined by the same boundary criteria.

Occurrence. 2340–? m in Well BY7-1-1, 2002–2191 m in Well KP6-1-1, and 1402–1498 m in Well KP9-1-1; Zhujiang Formation.

Age. Early Miocene, 17.62–19.09 Ma.

Zone M2

Definition. The top of M2 is defined by the LAD of *Globoquadrina binaiensis*. The base of M2 is defined by the LAD of *Paragloborotalia kugleri*.

Discussion. The zonal marker *Globoquadrina binaiensis* occurs in Well KP6-1-1 and Well KP9-1-1, showing very low abundance. As in Wade *et al*. (2011), the base of M2 is marked by the LAD of *Paragloborotalia kugleri*, which is only recorded in Well BY7-1-1 and Well KP6-1-1, but not in Well KP9-1-1 due to an extended interval below 1612 m barren of planktonic foraminifera. This zone is equivalent to the N5 of Qin (1996a).

Occurrence. ?–2781 m in Well BY7-1-1, 2191–2410 m in Well KP6-1-1; Zhujiang Formation.

Age. Early Miocene, 19.09–21.12 Ma.

Zone M1

Definition. The top of M1 is defined by the LAD of *Paragloborotalia kugleri*. The base of M1 is defined by the LAD of *Globigerina angulisuturalis*.

Discussion. Berggren *et al*. (1995b) and Wade *et al*. (2011) defined their Zone M1 as the total range of *Paragloborotalia kugleri*, with a calibrated age of 22.96–21.12 Ma. This zonal marker is very scarce in the study area. Its disappearance level is taken here as the top of M1 in Wells BY7-1-1 and KP6-1-1. The base of M1 is difficult to delimit for the studied wells because of the rarity of foraminifera and the inapplicability of the FAD bioevent for ditch cuttings samples. Qin (1996a) used the LAD of *Globigerina angulisuturalis* to mark the base of N4. According to Pearson and Chaisson (1997), the LAD of *Globigerina angulisuturalis* (23.3 Ma) occurred only slightly younger than the FAD of *Paragloborotalia kugleri* (23.7 Ma). Berggren *et al*. (1995b) dated the LAD of *Globigerina angulisuturalis* to 21.6 Ma, but Wade *et al*. (2011) calibrated this event to 20.94 Ma, even younger than the LAD of *Paragloborotalia kugleri*. This species is recorded only in Well BY7-1-1, and disappears at 3000 m, much lower than the level of the LAD of *Paragloborotalia kugleri*. We consider this event tentatively as the base of M1, equivalent to the N4 of Qin (1996a).

Occurrence. 2781–3000 m in Well BY7-1-1; Zhuhai Formation.

Age. Early Miocene, 21.12–? Ma.

4 Summary

A planktonic foraminiferal zonation for the Miocene to Pliocene succession in the Pearl River Mouth Basin is presented based on analysis of three wells (BY7-1-1, KP6-1-1 and KP9-1-1). Nineteen planktonic foraminiferal zones have been recognized, 14 zones (zones M1–M14) for the Miocene and 5 zones (zones PL1–PL5) for the Pliocene. The zonation is correlated with previously published biostratigraphic subdivisions of the Neogene succession in the PRMB and with international standard foraminiferal zonations. The zonal boundaries are mostly defined by the LADs of zonal taxa of planktonic foraminifera, which are more reliable than the FAD events for ditch cuttings sampling. The change in coiling events of *Globorotalia menardii* (s.l.) are also used to mark the zonal boundaries in the Late Miocene, where LAD events are not available. The *Fohsella fohsi* group, comprising useful taxa for delimiting zonal boundaries of the Middle Miocene in other areas, shows a poor record within the Pearl River Mouth Basin due to unfavorable ecological conditions, and is not applicable for the studied wells. Different from previously reported zonal scheme in the PRMB, the present zonation is based on correlation with the updated standard planktonic foraminiferal zonation of Wade *et al*. (2011), with absolute ages calibrated to the time scale of Lourens *et al*. (2004).

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